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Epoxy lignin-reinforced rosin wood coatings for improved strength and durability

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Abstract
The current study investigates the development of high-performance, environmentally friendly wood coatings using bio-derived epoxy lignin and rosin components. Lignin extracted from banana pseudo-stem through the kraft process was chemically modified and cross-linked with epoxy resin and natural rosin to formulate a biodegradable wood coating with enhanced durability. The incorporation of lignin not only promotes eco-friendliness but also contributes to thermal stability and mechanical reinforcement due to its aromatic-rich structure. Thermogravimetric analysis (TGA) of the developed coating revealed multiple degradation stages, with significant thermal stability observed up to 400 °C, confirming strong crosslinking interactions. FTIR analysis confirmed the successful formation of ester and ether linkages, as evidenced by prominent peaks at 1737 cm^{-1} and 1235 cm^{-1}, respectively. Compared to unmodified kraft lignin, the epoxy lignin-rosin coating exhibited increased hydrophobicity, improved adhesion, and resistance to thermal degradation, making it a suitable candidate for wood protection applications. This bio-based formulation provides a promising alternative to synthetic coatings, aligning with green chemistry principles and circular economy objectives.

Keywords: Kraft lignin, epoxy lignin, rosin, wood coating, biodegradable

1. Introduction
Wood coatings play a protective role by forming a layer against environmental factors like moisture, UV radiation, and biological degradation. They also contribute to the aesthetic appearance and durability of wooden structures [1, 2, 3]. Preventing wood from swelling and shrinking, which can lead to cracking and warping [4]. Synthetic wood coatings are typically composed of polyurethane resins, petroleum-based solvents, aldehydic resins, and external coloring agents or synthetic pigments. While these formulations offer excellent surface durability and weather resistance [5], they are associated with the release of volatile organic compounds (VOCs) notably isocyanates during application. These VOCs pose significant health risks, including respiratory irritation, skin allergies, and eye discomfort [6, 7, 8]. Moreover, such coatings often require chemical curing agents like zirconium octoate, cobalt naphthenate, or amine-based UV stabilizers, further increasing toxicity and environmental impact [9]. These substances can be absorbed by plants and animals, remain in the environment for a long time, and build up in soil and water. Some UV stabilizers, such as those based on benzotriazole or benzophenone, can partition into sediment or suspended particulate matter and are hydrophobic, which increases their impact on their surroundings [10].
In contrast, the epoxy lignin-based wood coating developed in this study utilizes plant-derived rosin as the main film-forming resin, ethanol as an eco-friendly solvent, and epoxy lignin as a natural crosslinking and reinforcing agent. The lignin, extracted from plant biomass, not only provides structural enhancement but also acts as a natural UV stabilizer due to its aromatic and phenolic structure. Lignin is a heterogeneous, amorphous polymer composed primarily of three phenylpropanoid units**.** Its complex structure includes functional groups such as phenolic hydroxyls**,** carbonyl groups, and conjugated double bonds, which act as effective chromophores**.** These features enable lignin to efficiently absorb ultraviolet (UV) radiation**,** particularly within the 250-400 nm range [11]. FTIR spectroscopy can be used to analyse the chemical structures of epoxy, lignin, and rosin-based wood coatings. Key features in the FTIR spectra include epoxy groups (around 900 cm^{-1}) [12]. Unlike synthetic pigments, the bio-coating maintains the natural transparent brown hue of the wood surface, eliminating the need for external colorants. Additionally, rosin, a biodegradable resin, contributes to moisture resistance and surface protection, while maintaining a low environmental footprint.

Utilizing lignin and rosin encourages the use of renewable resources and reduces dependency on fossil fuels [13]. This makes the epoxy lignin-based formulation a safer and more sustainable alternative to conventional wood coatings.

2. Methodology

2.1 Materials and Methods

Lignin was extracted from locally sourced banana pseudo-stem fibers using the alkaline pulping method**.** The fibers were treated with sodium hydroxide (NaOH) under controlled temperature and agitation to break down the lignocellulosic matrix and isolate the lignin. The extracted lignin was filtered, neutralized, and dried for further modification. Plant-derived rosin was used as the primary natural resin in the wood coating formulation. Its film-forming ability and tackiness made it suitable for creating a continuous protective layer on wooden surfaces [14]. Ethanol was employed as a green solvent to dissolve both rosin and lignin components, allowing for uniform application and efficient spreading of the coating formulation on wood substrates. The synthesized epoxy lignin was crosslinked with natural rosin used as a UV-protective component and polymeric properties in the wood coating formulation.

2.2 Epoxy Lignin Synthesis and Formulation

Epoxy lignin was synthesized by modifying kraft lignin through a reaction with epichlorohydrin under alkaline conditions [15]. The procedure was carried out as follows:

3 g of kraft lignin was placed in a round-bottom flask, and 15 g of 20% sodium hydroxide (NaOH) solution was added. The mixture was stirred continuously on a magnetic stirrer for 30 minutes to ensure complete dissolution of lignin. 30 g of epichlorohydrin was gradually added to the lignin-NaOH solution with continued stirring. The mixture was stirred for an additional 10 minutes to initiate the epoxidation reaction. The reaction mixture was heated to 70 °C and maintained at this temperature for 7 hours under reflux using a reflux condenser**,** with continuous stirring throughout the reaction period. Upon completion of the reaction, the mixture was allowed to cool to room temperature while stirring was continued to prevent any precipitation. The cooled reaction mixture was then neutralized using a 20% sodium dihydrogen orthophosphate (NaH_2PO_4) solution until the pH was adjusted to neutral (pH 7). The neutralized product was filtered**,** and the solid phase was thoroughly washed with deionized water 4-5 times to remove residual salts and unreacted impurities. The purified epoxy lignin was dried in a hot air oven at 30 °C until a constant weight was achieved. The final dry product was stored in an airtight container for use in subsequent wood coating formulations.

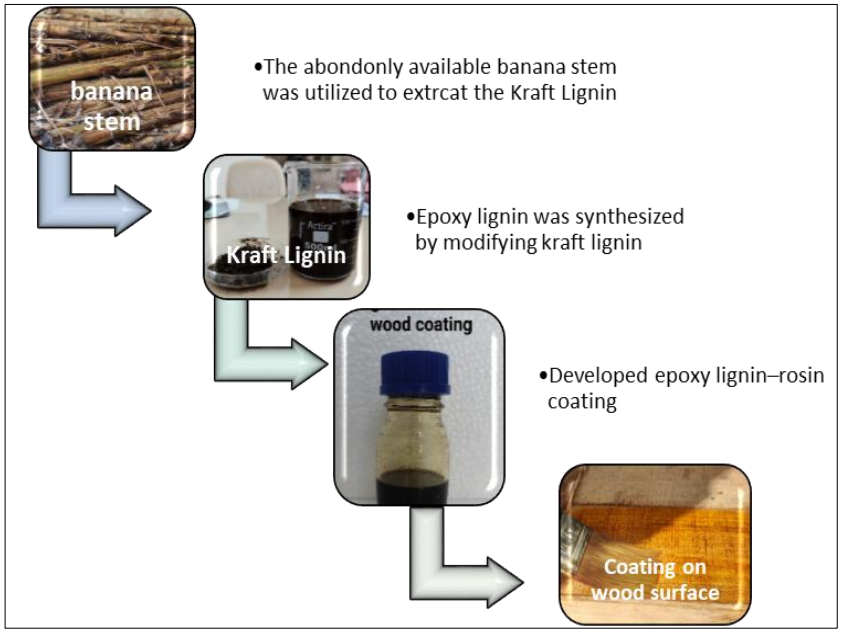
2.3 Preparation of Epoxy Lignin-Rosin Wood Coating Formulation

The wood coating formulation was prepared by crosslinking epoxy-modified lignin with plant-derived rosin using ethanol as a solvent medium. Rosin is a resinous substance produced from pine trees, contains a high concentration of resin acids with both hydroxyl and carboxyl groups [16]. Epoxy ring of epoxy lignin undergoes ring-opening in the presence of carboxylic acid groups of rosin to form β-hydroxy ester linkages. These reactions lead to a covalently bonded network, enhancing the mechanical strength and film stability of the coating. Residual phenolic hydroxyl groups in lignin may form hydrogen bonds with polar groups in rosin, contributing to additional physical reinforcement [17]. The procedure was carried out as follows:

10 g of synthesized epoxy lignin was dispersed in 100 g of ethanol. The mixture was gently heated with continuous stirring to ensure complete dissolution of the lignin. The solution was then filtered to remove any undissolved particles, yielding a clear lignin-ethanol filtrate. Separately, 50 g of plant-based rosin was melted using indirect heating under controlled conditions to avoid degradation. The temperature was maintained just above the softening point of rosin to achieve a uniform molten state. The prepared lignin-ethanol filtrate was slowly added to the molten rosin under continuous stirring. This ensured homogeneous mixing and effective crosslinking between the epoxy groups of lignin and the carboxylic functionalities of rosin. To optimize the coating viscosity and achieve a suitable film thickness, approximately 50% of the ethanol was evaporated under controlled heating and stirring**.** This step ensured the formulation had appropriate flow and film-forming properties for uniform application on wood surfaces. After being allowed to cool to room temperature, the finished product was stored in an airtight container for later application.

2.4 Application Procedure on Wood Surface

The prepared epoxy lignin-rosin coating formulation was applied to pre-conditioned wooden panels using standard coating techniques to evaluate its performance under practical conditions. Wood surface (size: 10 cm × 10 cm × 0.5 cm) were first sanded using fine-grit sandpaper to ensure a smooth, even surface and remove any surface contaminants. The wood surface was then wiped with a cloth soaked in ethanol to remove dust and grease and air-dried completely before coating. Two different application techniques were used to evaluate the coating behaviour. Firstly, the coating formulation was applied by Brushing Method using a synthetic bristle brush. A uniform layer was applied, and the panels were left to air dry at ambient temperature (25-28 °C). Secondly, the coating formulation was applied by spraying method using manual spray gun. After application, the coated panels were placed in a dust-free environment and allowed to dry at room temperature. Surface dry time and hard dry time were recorded according to standard coating test protocols. Bio-based coatings can be applied to joinery, furniture, outdoor applications, and other wood finishing and protection activities [18, 19].



3. Evaluation of Physio-Chemical Testing Parameters

The performance of the epoxy lignin-rosin wood coating formulation was evaluated following the procedure laid down in BIS Standard IS 3536:1999.

3.1 Drying Time

a. Surface Dry

The coated wood panel was placed in a vertical position and allowed to dry under standard atmospheric conditions (27±2 °C and 60±5% relative humidity), shielded from air currents and direct sunlight. After the designated time, the panel was laid horizontally, and approximately 0.5 g of fine glass beads was sprinkled evenly over the coating. After one minute, the panel was tilted to a 20° angle, and the surface was gently brushed using a camel hairbrush. The coating was considered surface dry if all the glass beads could be removed without causing any damage to the paint film.

b. Hard Dry

When a second coat could be applied following mild sanding without any film flaws like lifting, softening, or loss of adhesion, the coating was deemed hard dry. Furthermore, the second coat's drying time did not surpass the first coat's maximum drying time.

3.2 Consistency

The formulation was evaluated for flow behavior and uniformity. The coating exhibited smooth and uniform consistency, ensuring ease of application and effective film formation during brushing or spraying.

3.3 Finish

The formulation was applied on a prepared wood surface and allowed to dry under standard conditions. The coating formed a firmly adherent, flexible, and smooth film. The final finish was observed to be semi-glossy, with no signs of sagging, wrinkling, or uneven texture. The appearance and film quality were comparable to standard reference samples after 48 to 100 hours of drying.

3.4 Colour

The coating displayed a transparent brown tint, consistent with the natural color of lignin and rosin. Upon application, it imparted a warm, natural wood tone without requiring any external coloring agent.

3.5 Scratch Hardness

The dried coating was subjected to scratch resistance testing. It exhibited excellent scratch hardness, showing no visible scratches under applied pressure using a standard stylus method, thereby indicating mechanical strength and durability.

3.6 Resistance to Water

Coated panels were exposed to water immersion and water spray conditions. The formulation demonstrated good water resistance, with no blistering, peeling, or discoloration observed after exposure, confirming its suitability for wood protection in humid or damp environments.

3.7 UV-Visible Spectral Analysis

To assess the UV absorption capacity of the epoxy lignin-rosin-based wood coating, UV-Vis spectroscopy was conducted in the 200-500 nm range using a UV-1800 Series spectrophotometer in absorbance mode with a slit width of 1.0 nm.

3.8 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis was conducted to evaluate the thermal stability and decomposition profile of the crosslinked epoxy lignin-rosin wood coating**.** The analysis was carried out in a nitrogen atmosphere, and the weight loss of the sample was recorded as a function of temperature.

3.8 Fourier Transform Infrared Spectroscopy (FTIR)

Comparative Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted for banana lignin, epoxy lignin and epoxy lignin-rosin wood coating in Perkin Elmer Spectrum 2 in the range from 4000 cm^{-1} to 400 cm^{-1} to identify the functional groups present in the modification reaction.

4. Results and Discussion

4.1 Drying Time Performance

The epoxy lignin-rosin coating demonstrated significantly faster drying characteristics compared to synthetic coatings. Surface dry time was recorded at 30 minutes, and Hard dry

time was achieved within 4 hours, while in contrast, the conventional system required 90 minutes and 12 hours respectively. This notable reduction in drying time can be attributed to the low molecular weight solvent (ethanol) and the efficient film-forming ability of the lignin-rosin network. The epoxide groups in modified lignin facilitated rapid crosslinking, leading to quicker solidification.

4.2 Consistency and Film Finish

The epoxy lignin-rosin formulation exhibited a smooth and uniform consistency, enabling easy application by both brushing and spraying methods. The final film dried to a semi-gloss, transparent brown finish with no signs of wrinkling, sagging, or phase separation. The visual appeal of the coating, enhanced by the natural brown tint of lignin, supports its potential as a natural wood colorant without the use of external pigments.

4.3 Scratch Hardness

The coated panels exhibited no visible scratches when tested with a standard scratch stylus, confirming excellent mechanical resistance. This enhanced hardness is due to the rigid aromatic structure of lignin and its covalent crosslinking with rosin, resulting in a dense and durable polymer network.

4.4 Flexibility and Adhesion

Flexibility and adhesion tests confirmed that the bio-based coating passed without any cracking or peeling. The good interfacial bonding between the coating matrix and wood substrate is attributed to the hydroxyl and carboxyl groups in rosin and lignin, which likely interact with cellulose on the wood surface.

4.5 Water Resistance

The coated surfaces exhibited excellent resistance to water, with no blistering, peeling, or whitening observed after immersion. The hydrophobic nature of rosin, reinforced with the lignin matrix, imparts strong moisture barrier properties, suitable for protective wood applications in both indoor and semi-outdoor settings [20, 21].

Table 1: Experimental observations against synthetic wood coating

Testing	Lignin based Wood Coatings	Existing Wood Coatings
Drying time		
1. Surface dry	30 min	60 min
2. Hard dry	4 hr	10 hr
Consistency	Smooth and Uniform	Smooth and Uniform
Finish	Smooth and transparent	Smooth and transparent
Colour	Transparent Brown after applying on wood surface.	Transparent Brown after applying on wood surface.
Scratch Hardness	No such scratch.	No such scratch.
Flexibility and adhesion	Passed the test	Passed the test
Water resistant	Excellent	Excellent

4.6 UV-Visible Spectral Analysis

The obtained spectrum (Figure 1) shows a major absorbance peak at 435.60 nm was observed, with an absorbance intensity of 3.986 AU**,** which can be attributed to conjugated aromatic groups and phenolic structures present in epoxy-modified lignin. These chromophoric groups (e.g., phenylpropane units, conjugated double bonds, and carbonyls) are responsible for effective UV light absorption in the 250-450 nm range [22]. The high absorbance confirms the UV shielding capability of the coating, which is beneficial for enhancing the photostability of wood surfaces exposed to sunlight. The UV-Vis analysis confirms that the incorporation of epoxy lignin into the rosin-based formulation significantly improves its UV-protective properties, making it a bio-based alternative to synthetic coatings.

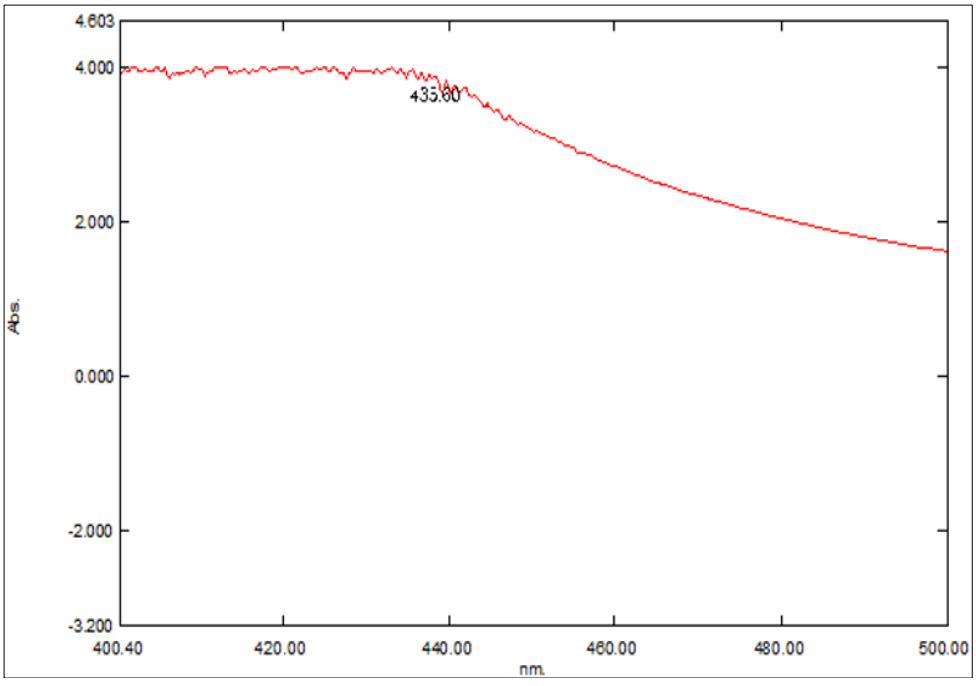


Fig 1: UV-Vis spectroscopy

Table 2: UV Absorption Characteristics of Epoxy Lignin-Rosin Coating

SN	Wavelength	Absorbance	Description
	435.60	3.986	Strong absorption in the visible-UV boundary region

4.7 Thermogravimetric Analysis (TGA)

The initial weight loss up to 112 °C is attributed to the evaporation of residual solvents, moisture, and volatiles**.** The second major decomposition event (217-298 °C) corresponds to the breakdown of lignin structures and rosin acids**,** which are sensitive to thermal cracking. The third and most pronounced degradation phase occurs at 402.30 °C**,** indicating the decomposition of highly crosslinked aromatic structures and epoxy linkages. Final degradation occurs beyond 440 °C, leaving behind minimal residual weight (2.96%)**,** which indicates good thermal resistance and low inorganic content. The TGA analysis confirms that the epoxy lignin-rosin-based wood coating exhibits multi-step thermal degradation behaviour**,** with a significant thermal stability up to 400 °C**.** The presence of aromatic epoxy-lignin components enhances the thermal resistance, making the coating suitable for high-temperature and outdoor applications [23, 24].

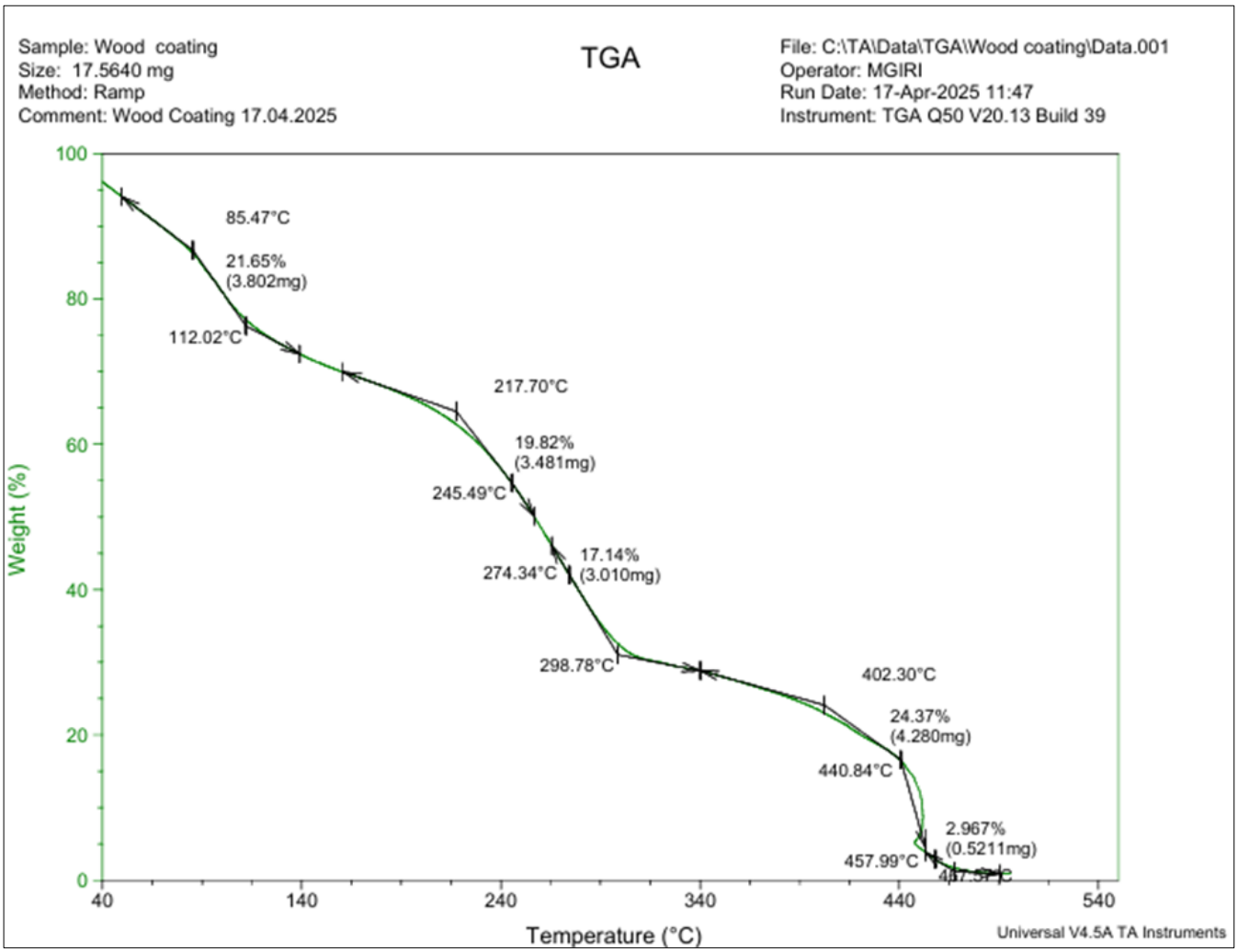


Fig 2: Thermogravimetric Analysis (TGA) of the epoxy lignin-rosin-based wood coating

Table 3: Thermal Degradation Stages of Epoxy Lignin-Rosin Wood Coating

Degradation Temperature	Wood Coating
T1	85.47 °C
T2	112.02 °C
T3	217.70 °C
T4	245.49 °C
T5	274.34 °C
T6	298.78 °C
T7	402.30 °C
T8	440.84 °C
T9	457.99 °C
T10	467.57 °C

4.8 Fourier Transform Infrared Spectroscopy (FTIR)

4.8.1 Comparative FTIR Analysis: Confirmation of Epoxidation in Lignin

Prior to modification, the FTIR spectrum of banana lignin shows important functional group vibrations that are indicative of the complex aromatic structure of lignin.

The O-H stretching vibrations of hydroxyl groups are represented by a broad band at about 3400 cm^{-1}. The C-H stretching of the methylene ($-CH_2$) and methyl ($-CH_3$) groups is responsible for the peaks located between 2922 and 2850 cm^{-1}. The lignin backbone's aromatic skeletal vibrations are indicated by peaks at 1600 cm^{-1} and 1510 cm^{-1}. Guaiacyl ring breathing in conjunction with C-O stretching is represented by a noticeable peak at about 1260 cm^{-1}. C-O stretching in

primary alcohols is represented by peaks in the 1030-1050 cm^{-1} range.

In comparison, the epoxy lignin spectrum, exhibits a number of noticeable alterations that signify effective epoxidation. Epoxide group formation is strongly indicated by the epoxy (oxirane) ring vibration, which appears as a new peak or increased intensity around 910-950 cm^{-1}. A decrease in hydroxyl band intensity at about 3400 cm^{-1} indicates that-OH groups are consumed during epoxidation. Peak shifts or modifications in the 1260-1050 cm^{-1} region involve C-O-C vibrations and may broaden or shift as a result of epoxy ring addition. Changes in the aromatic core's structure may also be indicated by more distinct ring breathing vibrations.

These spectral changes offer strong proof that the lignin structure has been successfully modified by epoxidation, rendering it more reactive and appropriate for rosin crosslinking. In comparison to conventional synthetic coatings, the resulting epoxy lignin-rosin system offers improved mechanical strength, thermal and UV resistance, and environmental safety, making it an ideal bio-based wood coating.

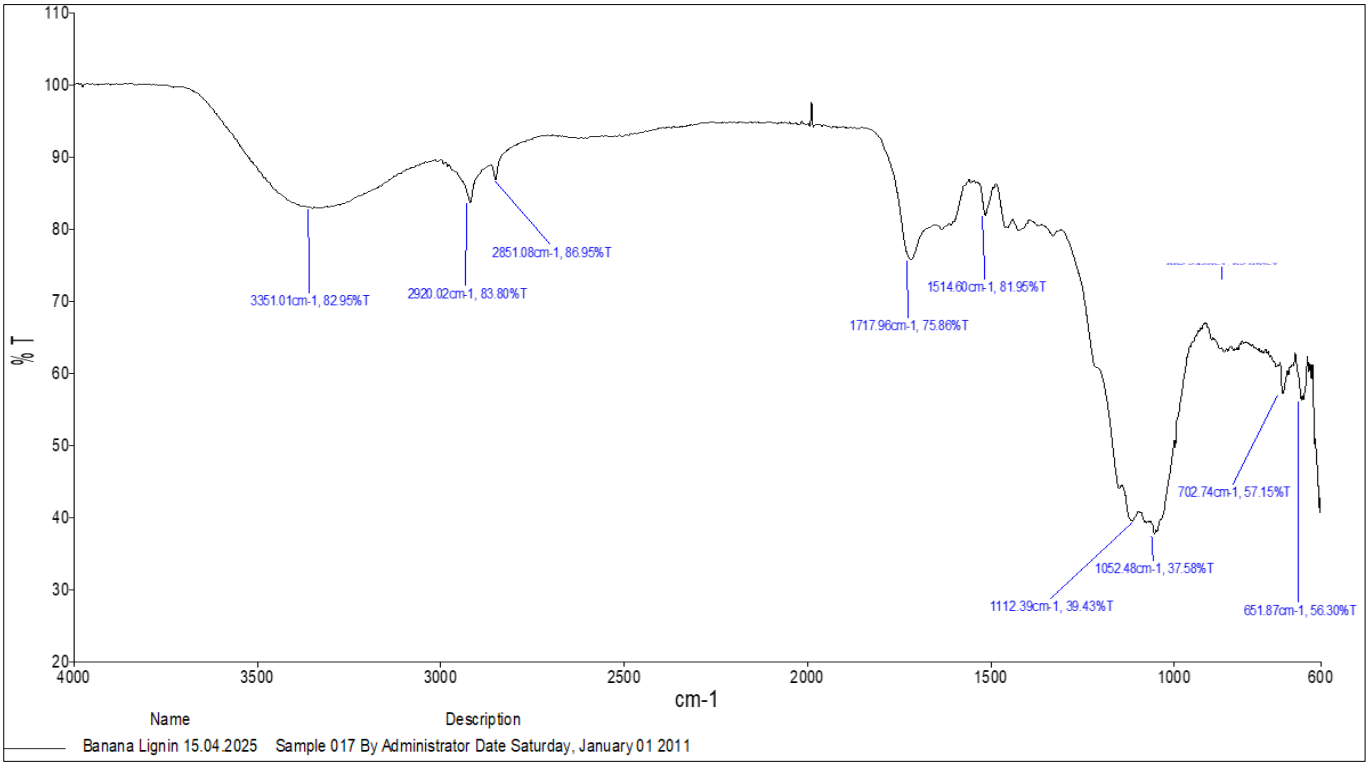


Fig 3: FTIR Spectrum of Banana Lignin

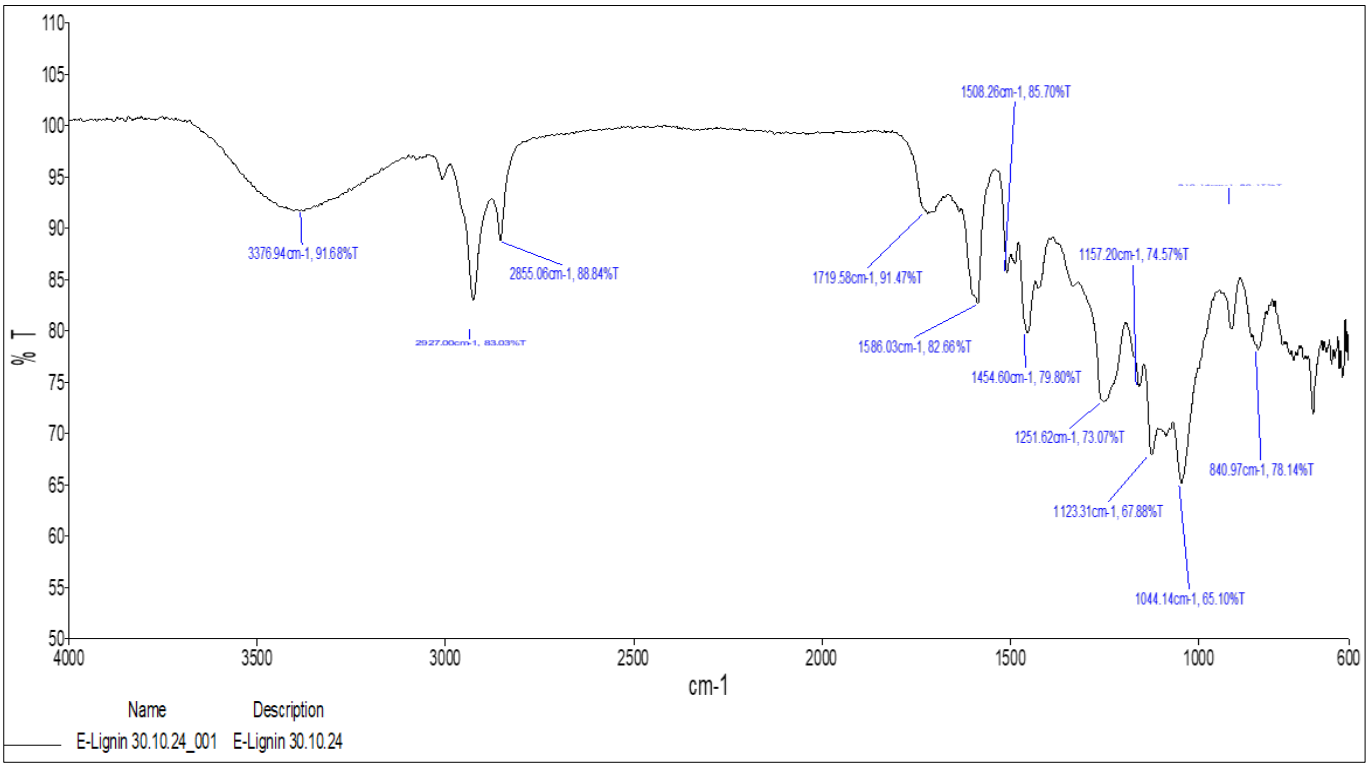


Fig 4: FTIR Spectrum of Epoxy Lignin

4.8.2 Comparative FTIR Analysis of Epoxy Lignin and epoxy lignin-rosin-based crosslinked wood coating

Broad O-H stretching 3337 cm^{-1} is still present in the comparison, but it has decreased, suggesting additional crosslinking. Stronger/new peaks at 1720-1735 cm^{-1} probably as a result of rosin's ester C = O stretching. The development of ether and ester linkages is supported by enhanced C-O-C and aromatic peaks (1030-1260 cm^{-1}). Absence or weakening of the epoxy peak between 910 and 950 cm^{-1} shows that the epoxy rings have undergone a crosslinking reaction. The successful crosslinking of the epoxy groups is indicated by the decreased epoxy peak in the FTIR spectrum of the epoxy lignin-rosin-based wood coating. The rosin integration is supported by the appearance of ester C = O peaks. Participation in the reaction is indicated by a decrease in hydroxyl groups. This demonstrates that epoxy lignin and rosin work well together to create a crosslinked polymer network, which is perfect for long-lasting, environmentally friendly wood coatings with improved mechanical and UV resistance.

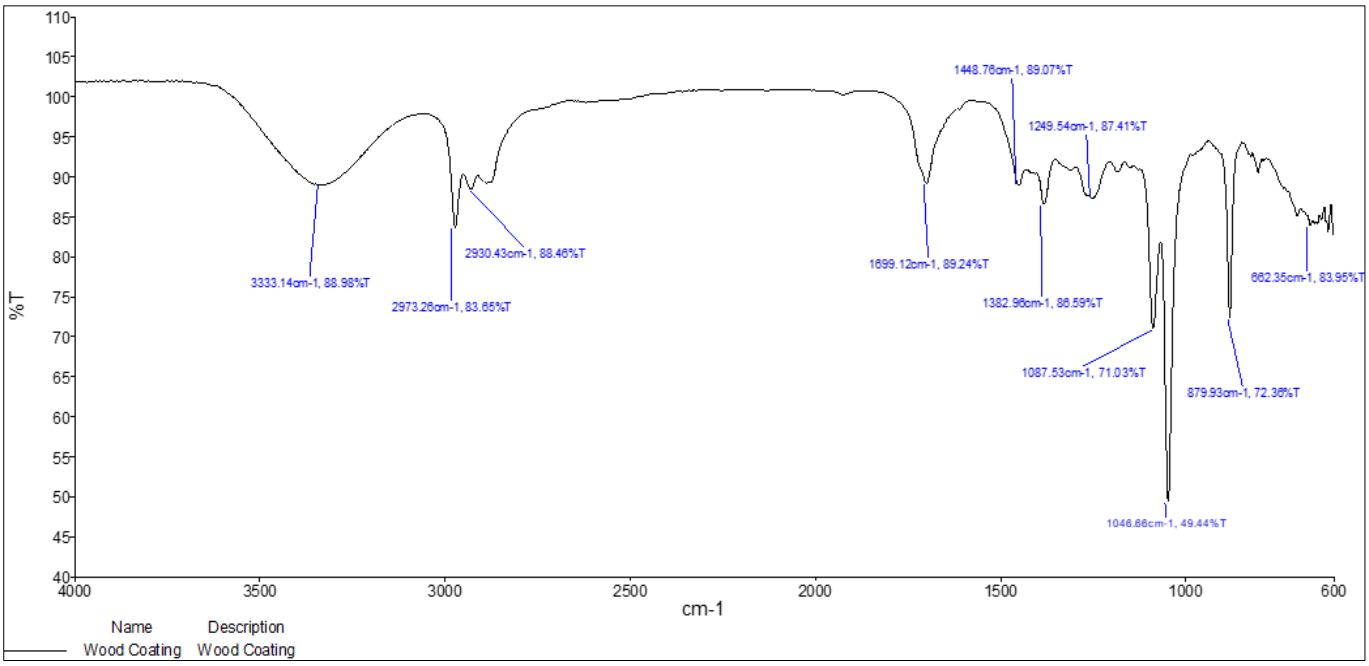


Fig-1: FTIR Spectrum of epoxy lignin-rosin-based crosslinked wood coating

5. Conclusion

The crosslinked wood coating made of epoxy lignin and rosin shows great potential as a sustainable alternative for synthetic coatings. The developed epoxy lignin-rosin wood coating system is made from renewable plant-based resources and has low toxicity, making it a safer option for the environment than synthetic coatings that emit volatile organic compounds (VOCs). Effective crosslinking with rosin is made possible by the chemical modification of lignin with reactive epoxy groups, which improves its mechanical strength, scratch resistance, and heat resistance. Furthermore, the coating exhibits superior oxidative and UV stability, which qualifies it for long-term wood protection. In line with green chemistry and the principles of the circular economy, this study emphasizes the potential of lignin as a value-added component in bio-based coating formulations and its applicability in sustainable material innovations.

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